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14. ABSTRACT

This briefing presented an overview of advanced concepts for launch at AFRL. It explored "the" launch problem and "the" nanoLaunch problem, then discussed advanced concepts for cost effective launch/nanoLaunch.

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An Overview of Advanced Concepts for Launch

Marcus Young

Jason Mossman

USC Engineering Honors Colloquium

Feb. 24, 2012

Outline

1. Advanced Concepts at AFRL

2. “The” Launch Problem

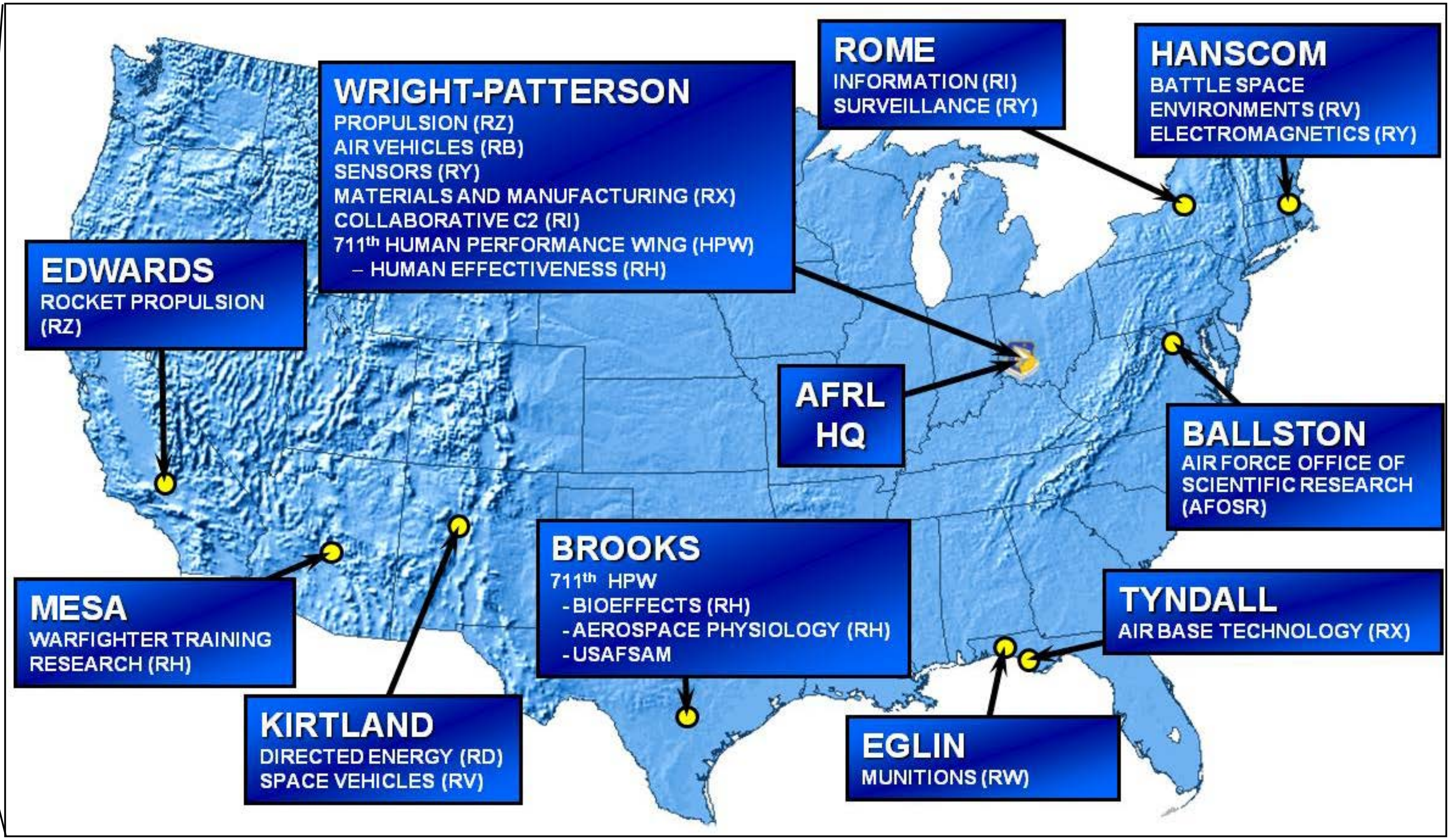
3. “The” nanoLaunch Problem

4. Advanced Concepts for Cost Effective Launch/nanoLaunch

1. Advanced Concepts at AFRL

- *Air Force Research Lab*
- *Advanced Concepts Group*
- *What is an Advanced Concept?*

Air Force Research Lab



Propulsion Directorate

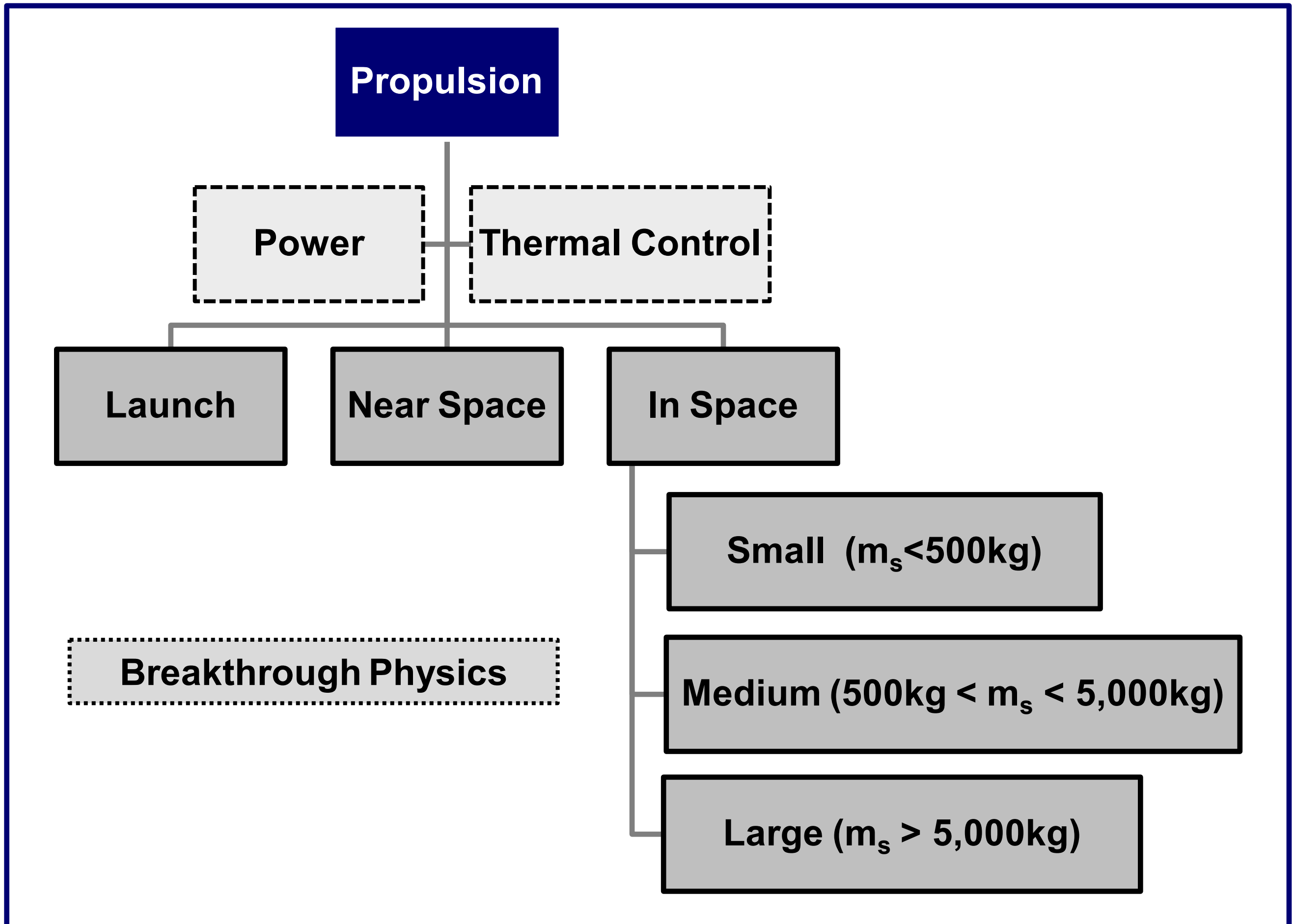
Aerophysics Branch

Advanced Concepts Group

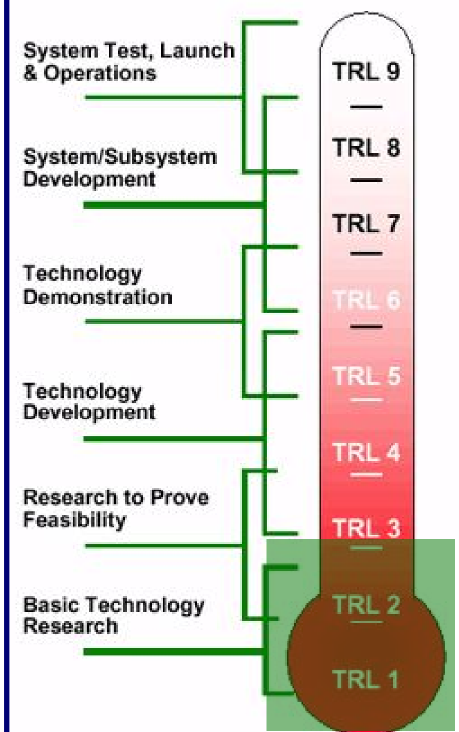
- AFRL Does: Research and Develop Advanced Tech.
- AFRL Does Not: Manufacture or Use Advanced Tech.

Advanced Concepts Group

"Enable Future AF Missions Through the Discovery and Demonstration of Emerging Revolutionary Technology"

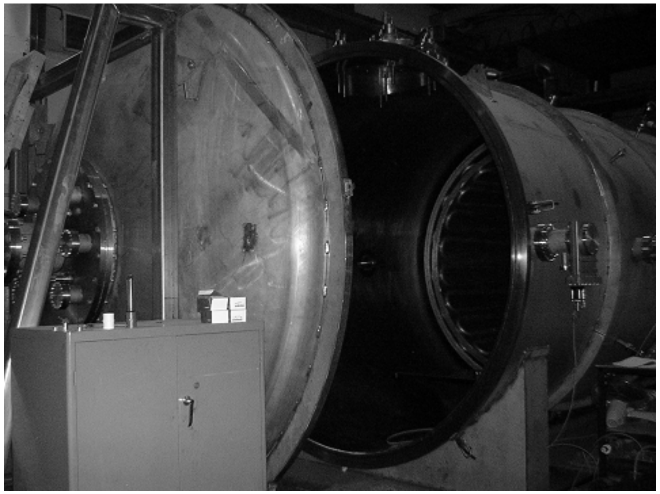


- **15-50 Years**
- **Technology Push**

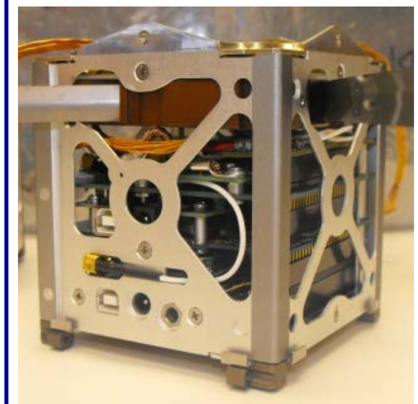


Advanced Concepts Group
USC Activities

CHAFF



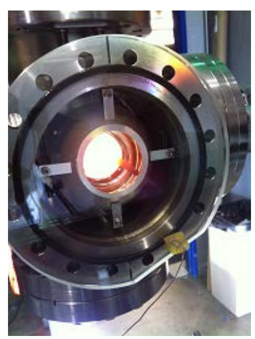
Cubesat Propulsion (Future?)



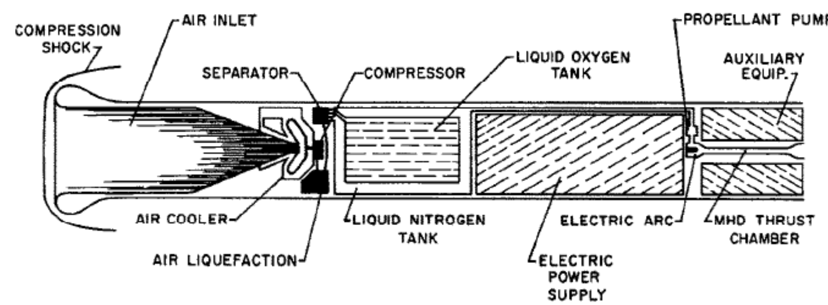
- Nanosat: m_p = 1-10kg.
- Cubesat: Adhere to specs.
- Lightweight
- Cheap.
- Fast.
- Simple.
- Risk O.K.
- Wrong Orbit.
- Limited/No Propulsion.

⇨ Significant DV Propulsion is Enabling.

HEATS

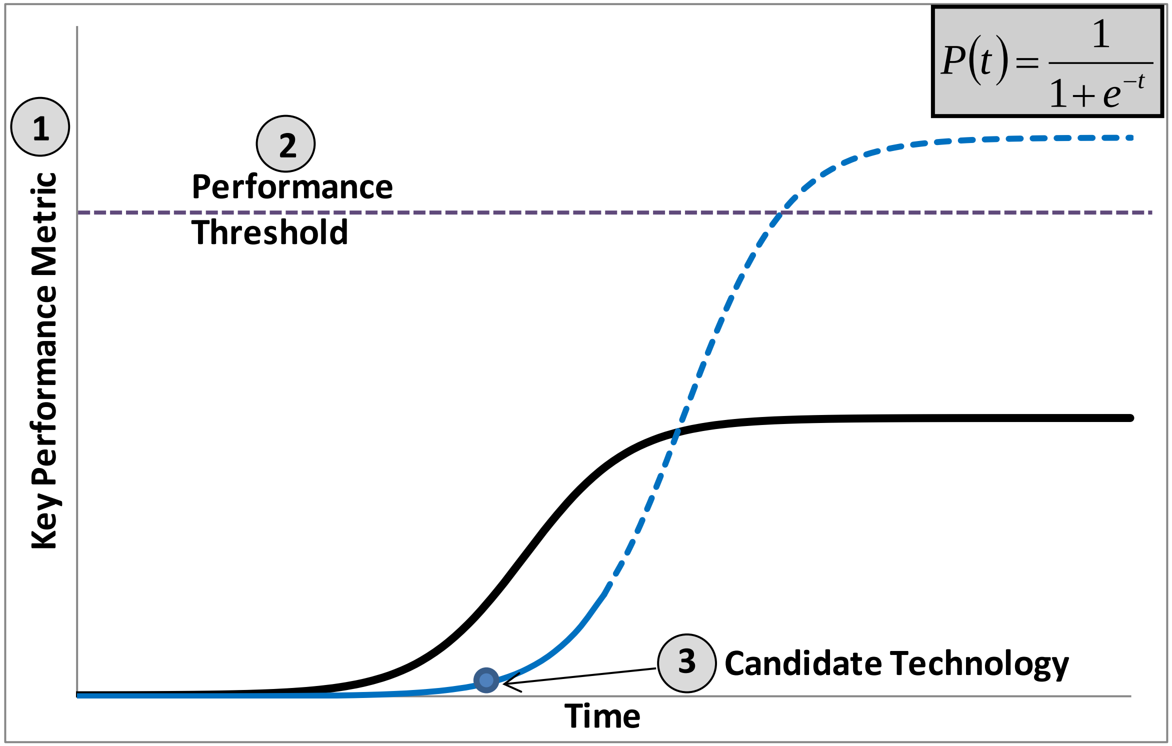


Air Breathing Satellite (Future?)

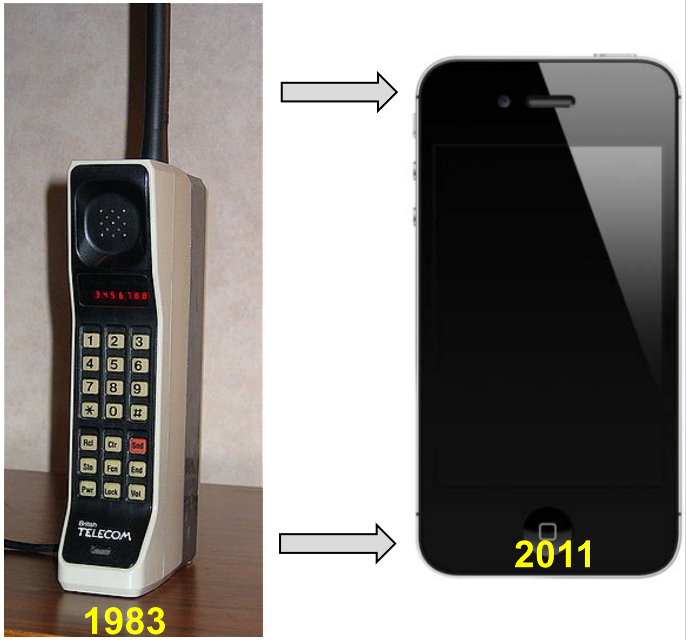


- Dip lower (150km) to collect propellant.
- Dramatic increase in achievable ΔV.
- Scooping at 7.8km/s is difficult problem…

Advanced Concept



Cell Phone Example



1. Identify Key Metric. *($/Performance)*
2. Identify Enabling Threshold. *(10x Reduction)*
3. Identify Technology Required to Cross Metric. *(Many)*

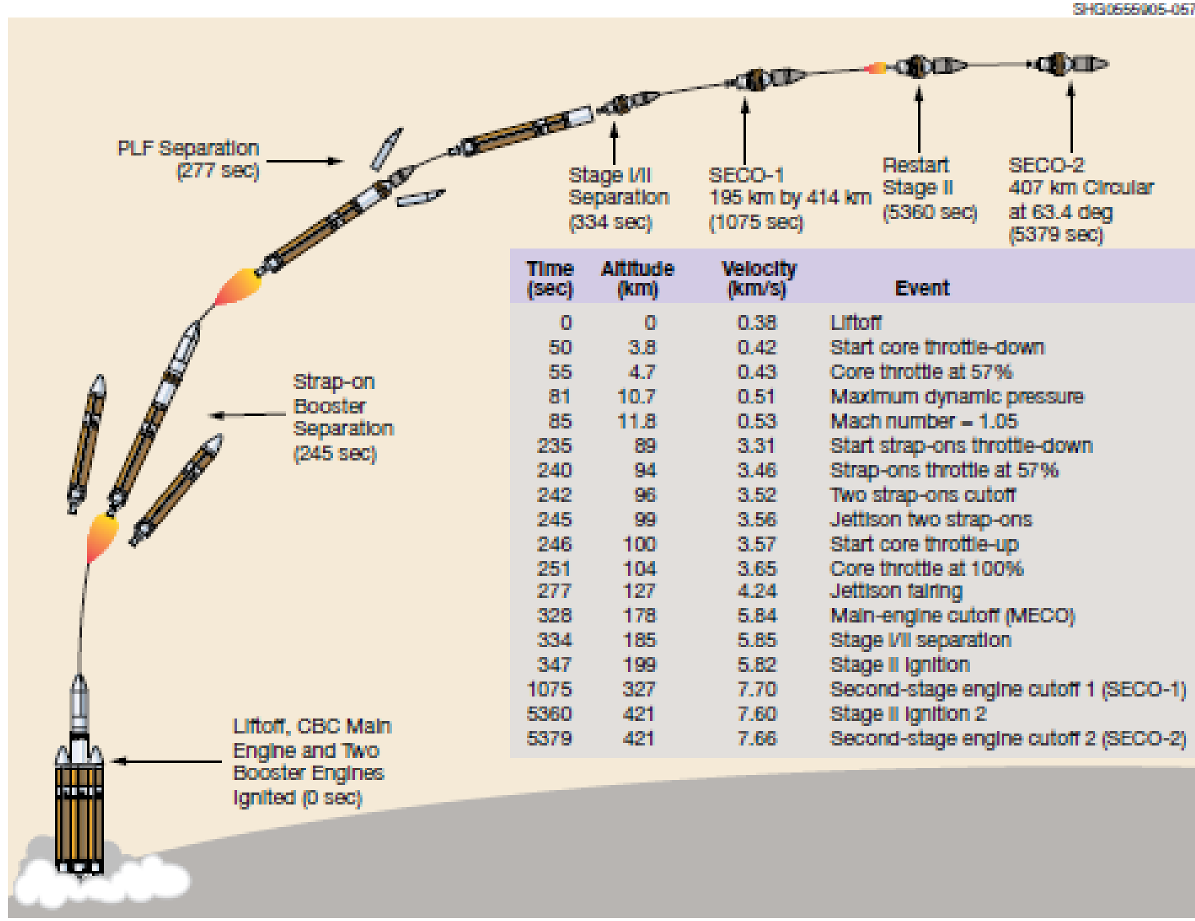
- Insufficient Modeling Available.
- Require Unknown Breakthroughs.

2. “The” Launch Problem

- *Space Operations Process*
- *Typical Launch Parameters*
- *Recent Launch Statistics*
- *Lessons Learned*

Delta IV Heavy Launch

Delta IV Payload Planners Guide
September 2007
06H0233



Time (sec)	Altitude (km)	Velocity (km/s)	Event
0	0	0.38	Liftoff
50	3.8	0.42	Start core throttle-down
55	4.7	0.43	Core throttle at 57%
81	10.7	0.51	Maximum dynamic pressure
85	11.8	0.53	Mach number = 1.05
235	89	3.31	Start strap-ons throttle-down
240	94	3.46	Strap-ons throttle at 57%
242	96	3.52	Two strap-ons cutoff
245	99	3.56	Jettison two strap-ons
246	100	3.57	Start core throttle-up
251	104	3.65	Core throttle at 100%
277	127	4.24	Jettison fairing
328	178	5.84	Main-engine cutoff (MECO)
334	185	5.85	Stage I/II separation
347	199	5.82	Stage II ignition
1075	327	7.70	Second-stage engine cutoff 1 (SECO-1)
5360	421	7.60	Stage II ignition 2
5379	421	7.66	Second-stage engine cutoff 2 (SECO-2)

Figure 2-6. Delta IV H Sequence of Events for LEO Mission (Western Range)

Typical Launch

Typical Launch Magnitudes

	Falcon I	Saturn V
Payload (LEO) [kg]	450	119,000
Cost [$]	$7M	$1.1B (2011$)
Cost/mass [$/kg]	$15,600	$9,200
Height [m]	22.25	110.6
Diameter [m]	1.7	10.1
Wet Mass [kg]	3.32×10^4	3.03×10^6
Payload Fraction	1.4%	3.9%
Th_{SL} [MN]	0.343	34
P_{throat} [GW]	0.85	130

- Responsiveness:
  - Now: years → Want: weeks/days.
  - Desert Storm: Sept. 1990 → Launch Feb. 1992!
  - Solids (Minotaur I) → Launch in Days.

Typical Launch Breakdowns

Energy Efficiency

$$\boxed{\eta_{en}\ (20\%)} = \eta_{\text{int}} \cdot \eta_{pr} \cdot \eta_{me} \cdot \eta_{dr} \cdot \eta_{g}$$

Mass Breakdown

$$M_{lo} = \boxed{M_{fuel}\ (85\%)} + \boxed{M_{str}\ (14\%)} + \boxed{M_{pay}\ (1\text{-}4\%)}$$

$ Efficiency

$10,000/kg

$$\$_{l} = \boxed{\$_{r\&d}\ (50\%)} + \boxed{\$_{ve}\ (30\%)} + \boxed{\$_{go}\ (20\%)} + \ldots \boxed{+\$_{en}\ (.01\%)}$$

- Launch Involves Extreme Numbers and is Extremely Difficult.
- Rockets Are an Inefficient and Expensive Way to Launch.
- Rockets Are All We Have.

Space Operations

<u>~10% costs due to launch</u>

- Small number of unique launches.
- Standing army for facilities/vehicles.
- ~~Increase total number of launches.~~
- Increase launch/vehicle (all fly same).
- Need competition.

<u>~25% costs due to spacecraft</u>

- Nearly all space hardware is unique.
- Extremely low risk tolerance.
- *Increase capabilities/mass.*
- *Expand cubesat paradigm.*
    - *-Well defined specification.*
    - *-Risk accepted.*

<u>~65% costs due to ground ops.</u>

- Large ground workforce.

→ *Automation, Simplification.*

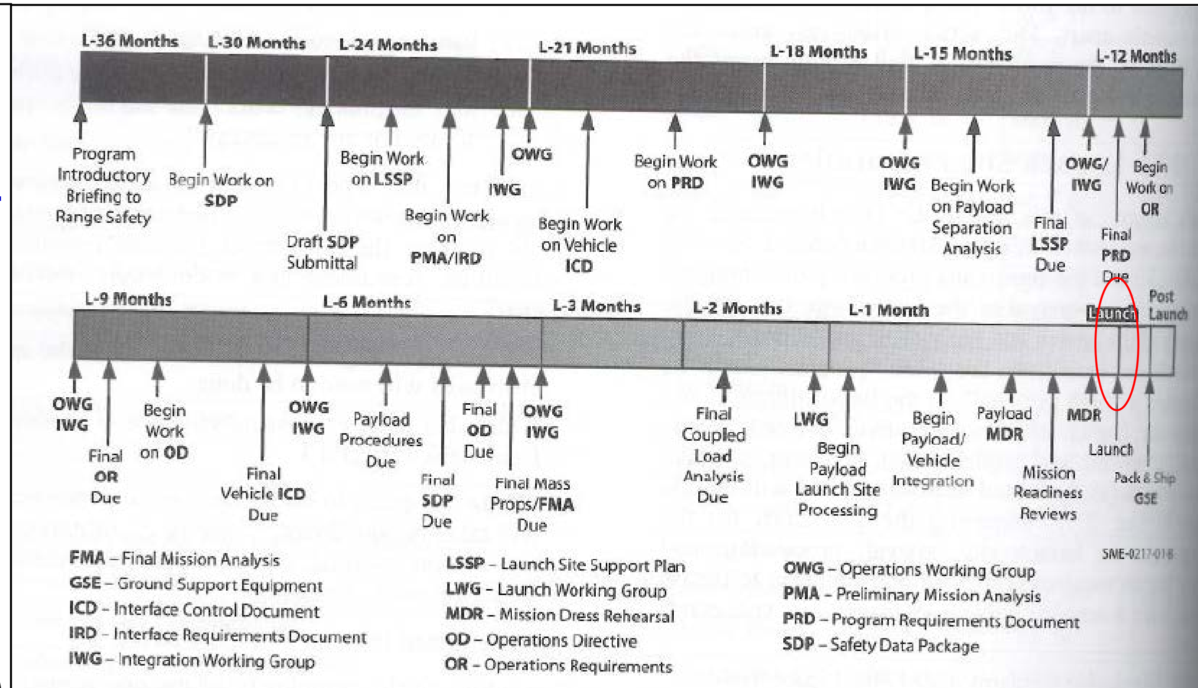
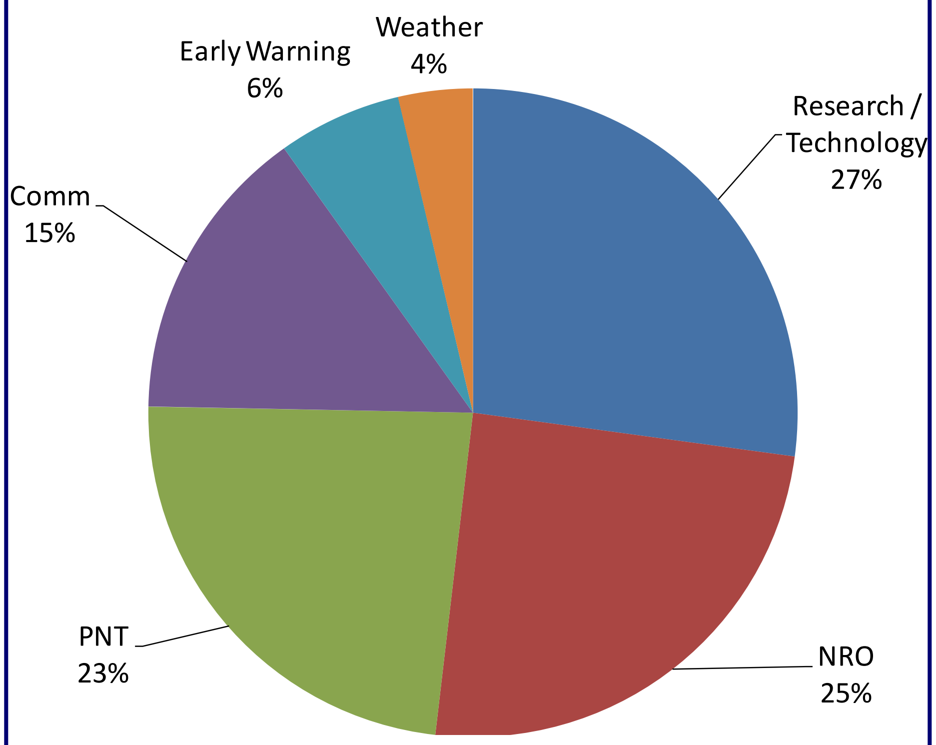


Fig. 27-2. Typical Launch Operations Timeline.

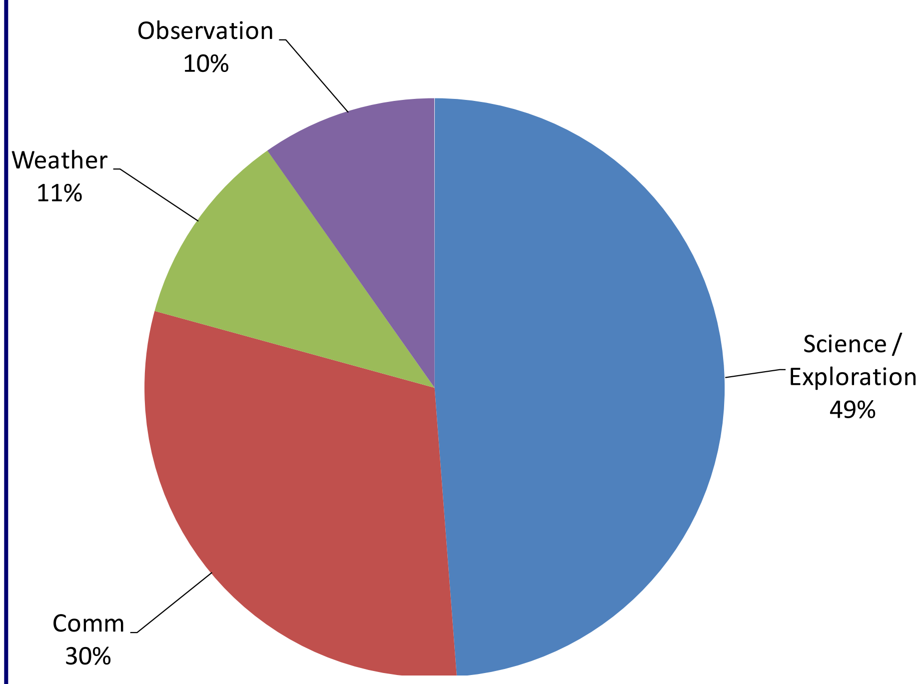
Space operations is much more than just the launch day.
Free launch → still 90% of space operation cost.
Cheap launch is a critical part.

MIL and CIV Space Why?

2000 – 2010 Launch Missions (Military)

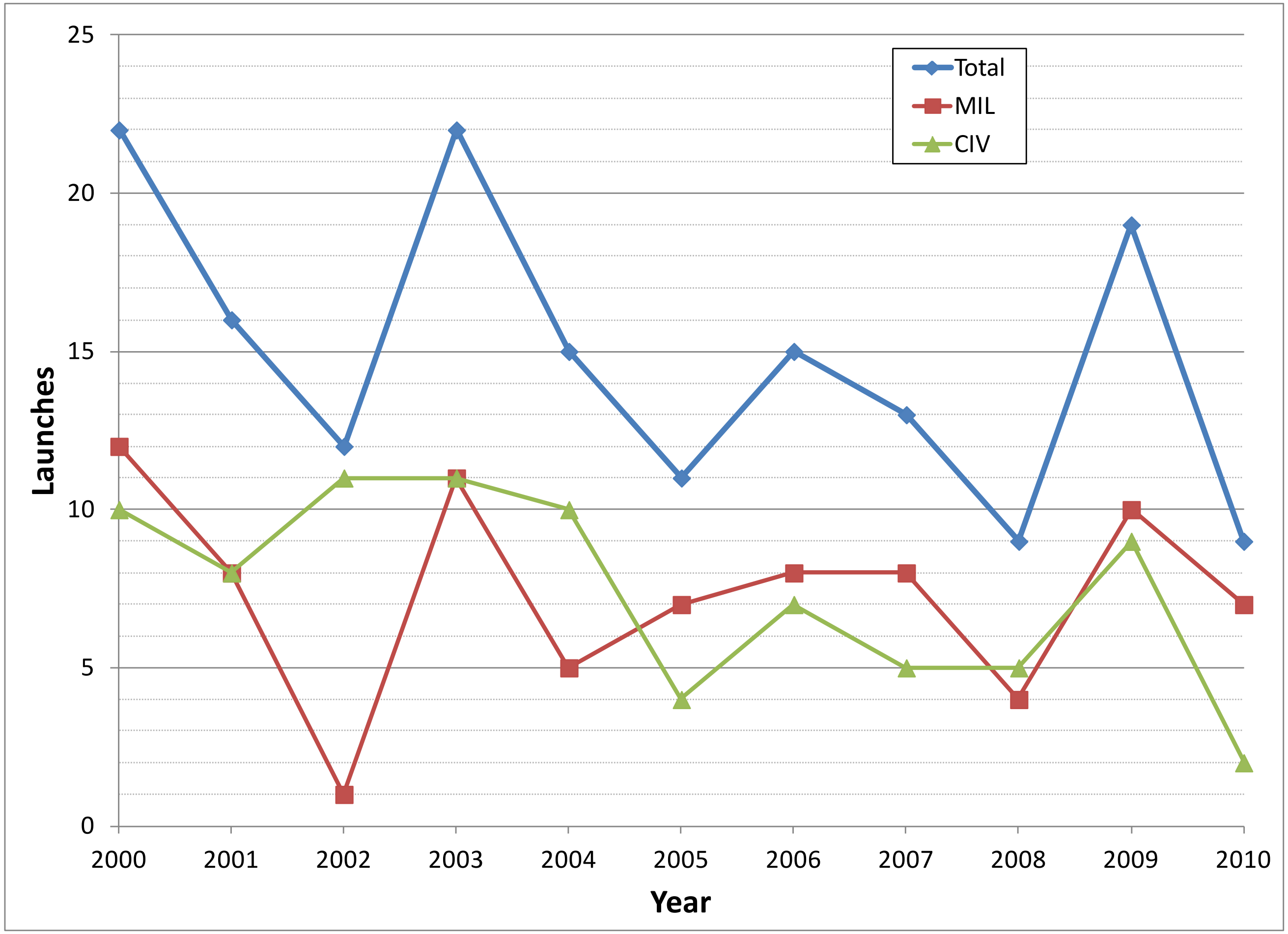


2000 – 2010 Launch Missions (Civilian)



- Wide Range of Applications for Both MIL and CIV.
- Core Metric is $ per Mission Performance.
- Launch is a Key Component of $.

MIL and CIV Space How Often?



2000–2010 U.S. Averages

MIL	7.4
CIV	8.0
(U.S.)	15.4/yr

Worldwide Launches

1957 – 2009	4,621
2006 – 2009	259
‘06-’09 avg.	~65

Large Missions

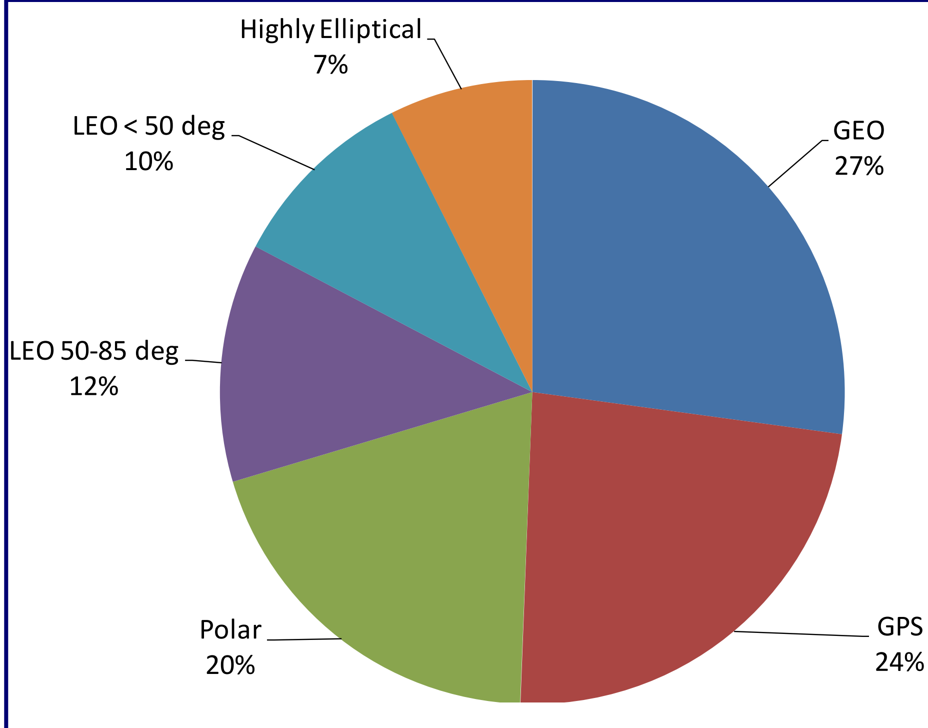
- Apollo → 13 (6 yrs).
- Shuttle → 135 (30 yrs).
- ISS → 105 (13 yrs).
- GPS → 62 (33 yrs).

- SBSP(GW) ~ 100 (<10 yrs)
- Virgin Galactic ~ 70 (suborb)

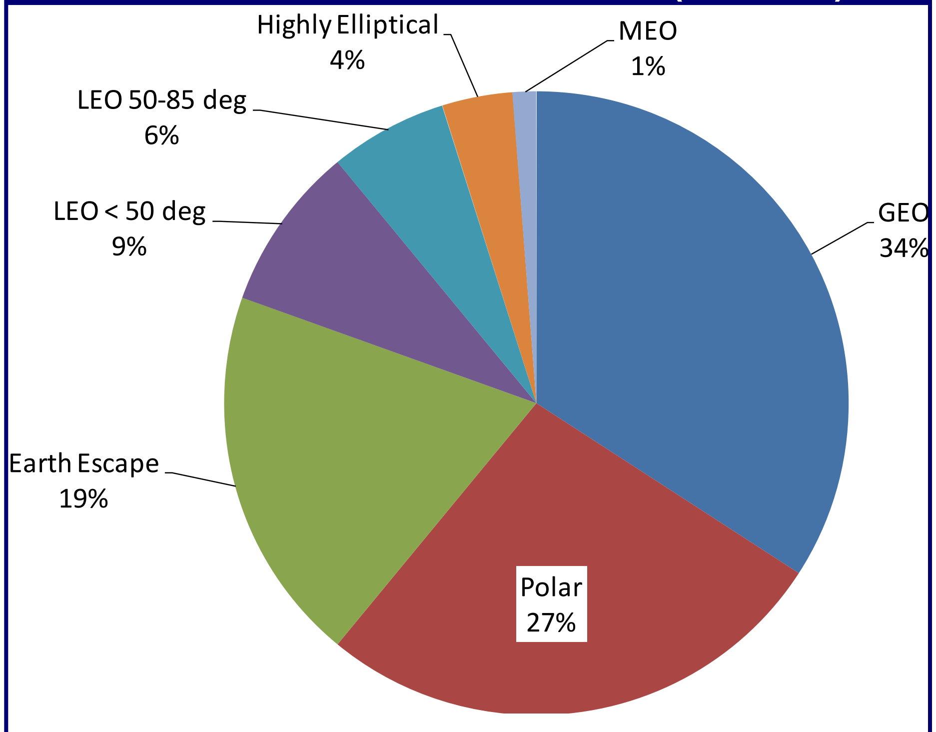
- ~15 Total US Launches/Year (1/4 of World). MIL & non MIL Roughly Equal.
- Historical Trends and Candidate Applications Require Few Launches.

MIL and CIV Space Where To?

2000 – 2010 Launch Destination (Military)



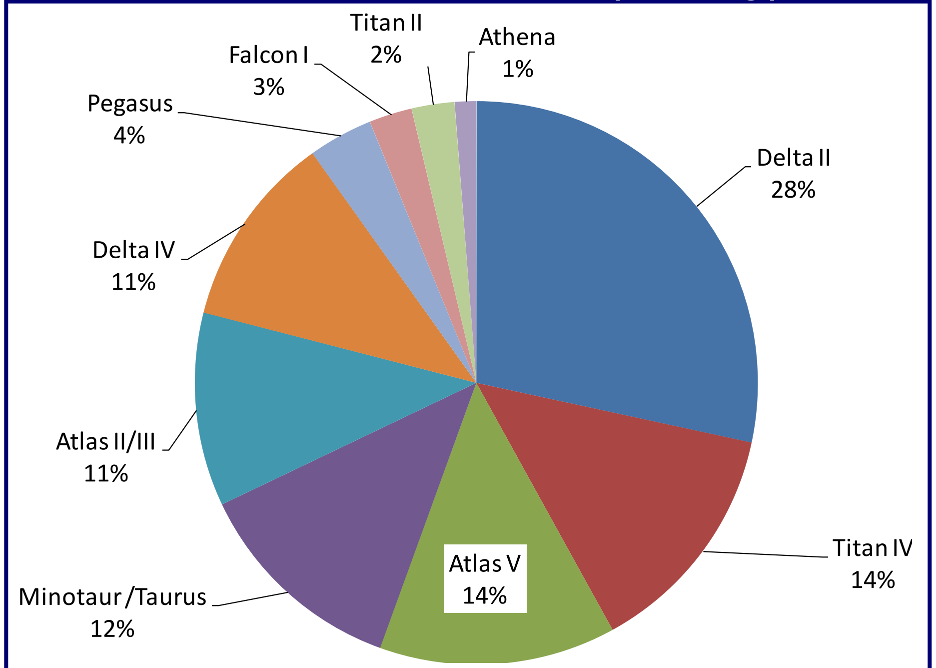
2000 – 2010 Launch Destination (Civilian)



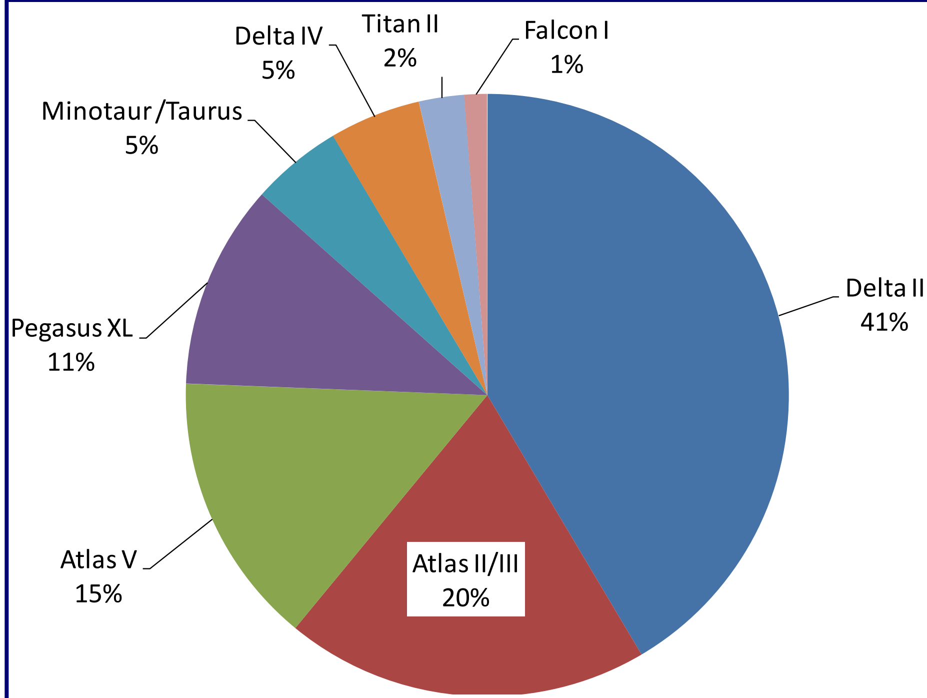
- Large Range of Destinations Required for Missions.
- Not Condensable to Single Site and Vehicle.

MIL and CIV Space How?

2000 – 2010 Launch Vehicles (Military)



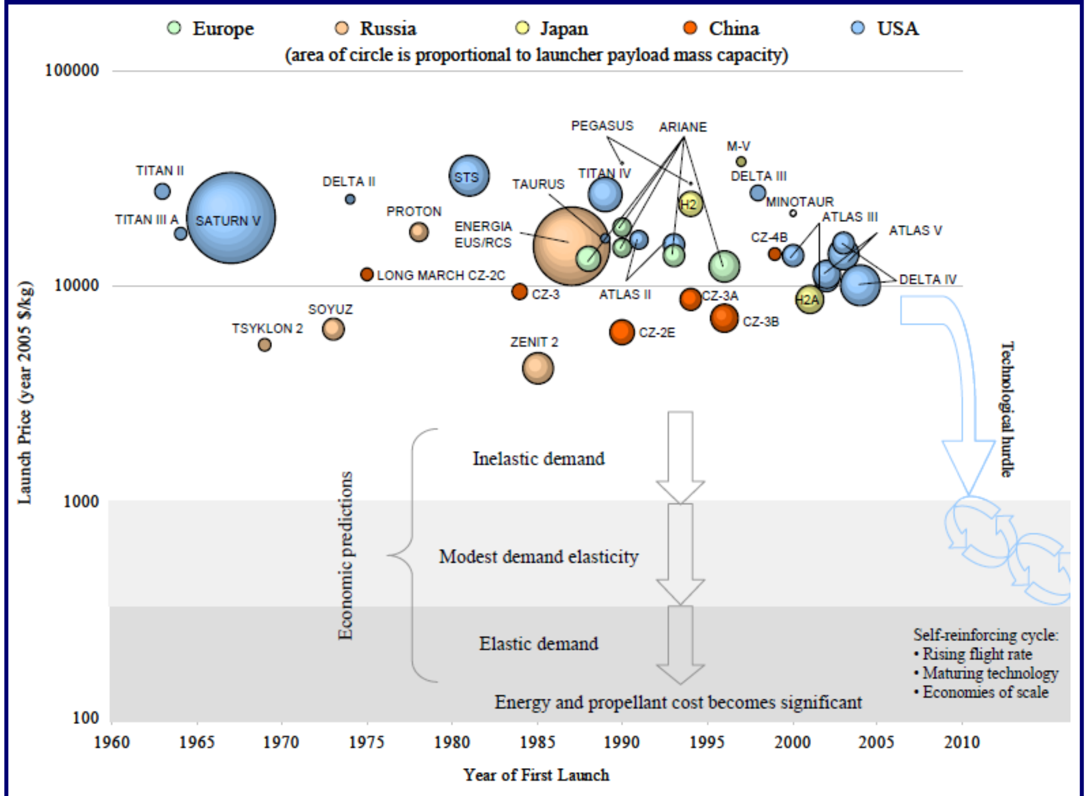
2000 – 2010 Vehicles (Civilian)



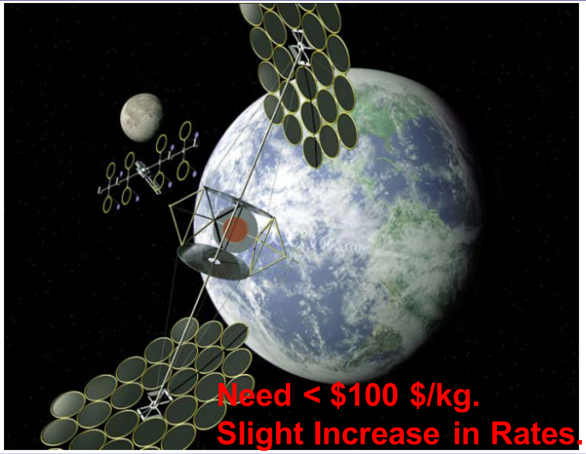
- ~10 Vehicles for MIL and CIV launches.
- No Launch Vehicle Used More than 5.7x per Year (Delta II).

"The" Problem Launch Costs

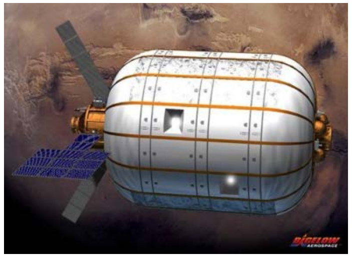
Historical Launch Costs (Parkin, 2006)



Space Based Solar Power



Space Tourism



- ¾ price for transport.
- $23M for 30 day stay.
- America's Space Prize.
- Man Rated!

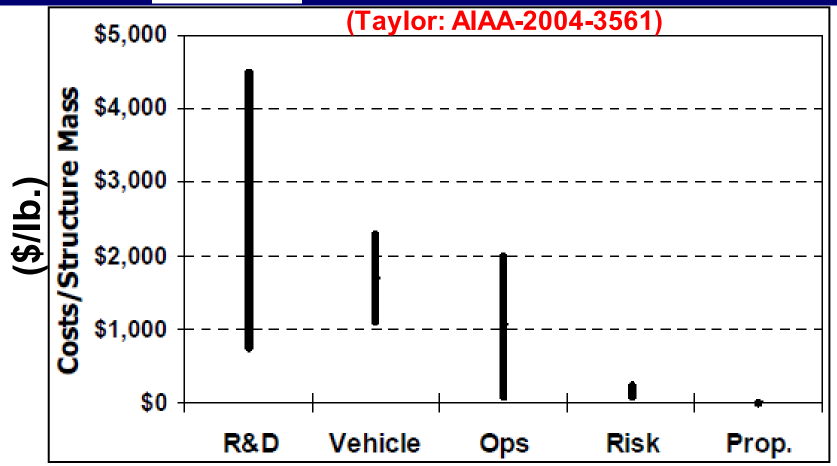
- 1/10 Cost May Yield Market Elasticity and Further Reductions.
- 1/10 Cost May Also Enable Candidate Markets.

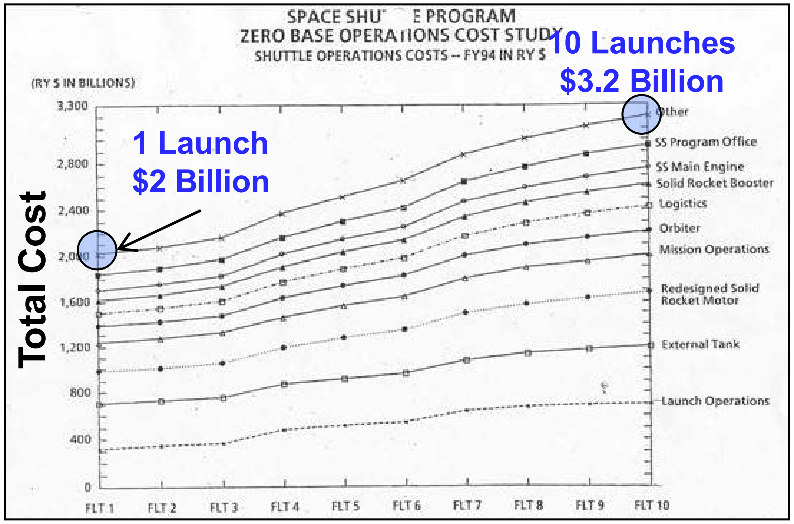
→**Reduce Launch Costs by One Order of Magnitude.** *(At Current Rates)*

Reducing Costs

Cost of Launch

(Taylor: AIAA-2004-3561)

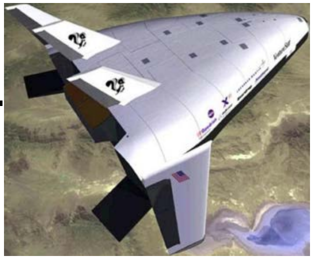




R&D, Vehicle, Operations, and LAUNCH RATE.

Common Solutions

- Reusability
  - -Payback (~10s).
  - -High Reliability.
  - -Shuttle: ~~"Weekly Launches"~~
  - -Inspect & Rebuild.
- SSTO
  - -LOx/LH_2: m_s < 10%
  - -Advanced Structure/Tank.
  - -Aerospike.
  - -Sensitive Design Space.

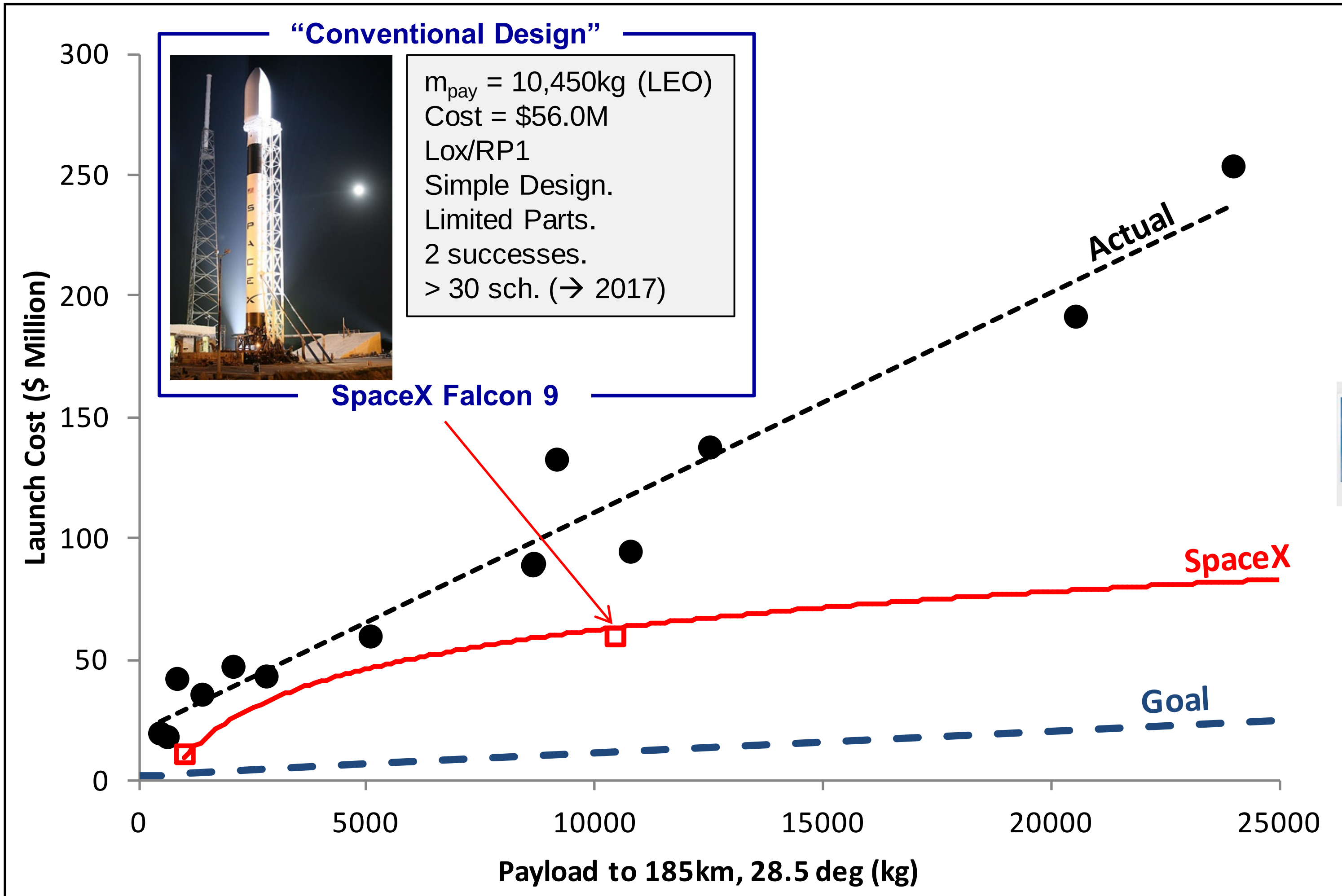


Reusable & SSTO do not guarantee $ savings.

Can We Avoid Launching?

•Reuse orbital mass	→ DARPA Phoenix.
	→ ~~MDA Corp.~~
•Avoid launching	→ Lockheed Martin HAA.

Recent and Future Options



$m_{p,LEO}$ = 6,100kg
(2016)

- Recent/Active Launch Vehicles Follow Trend and Haven’t Improved Towards Goal.
- Near-Term Solutions Hope to Demonstrate Improvement, but do NOT Achieve the Goal.

3. The nanoLaunch Problem

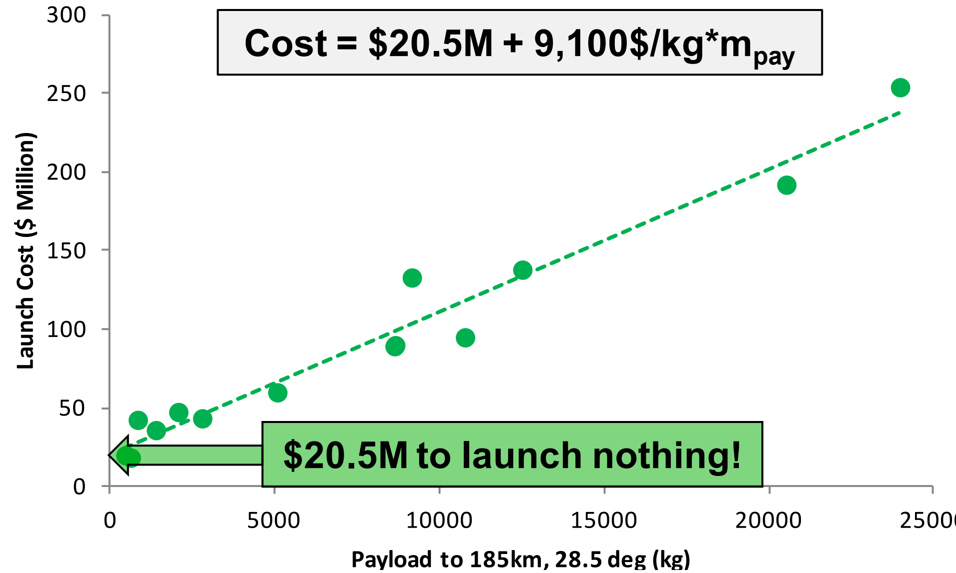
Nanolaunch Costs

Nanosatellite Operations (Cubesats)

- Nanosatellite: m_{sat} = 1 – 10kg.
- Cubesat: Adheres to specs.
  - -Simplified Design.
  - -Specified Release.
  - -System Unification.
- Very Short Time-Scales.
- Very Low Cost.
- Accept Higher Risk.
- Limited Functionality, Propulsion.
- Dropped off in Wrong Orbit with Little/No Propulsion.

Need Dedicated Nanolauncher.

- Must Maintain Paradigm
  - -Simple, Responsive, Very Low Cost
- BUT
  - -Cost/kg increases with decreasing size.
  - -Uncertainties → hard to accurately deliver.



- Real need for responsive, cost effective nanolaunch.
- Acceptable solution possible in near term.
- Better solution needed for long term.

"Conventional Design"

2-Stage NLV
10kg to 250km polar.
LOX/Densified C_3H_6.
d = 0.65m
h = 7m
Th_{s1} = 20kN
Isp_{s1} = 212s
Cost ~ \$1M.

Garvey Spacecraft

4. Advanced Concepts for Launch

New Combustion Reactants

- Advanced Propellants/Oxidizers
- Air Breathing Concepts

Onboard, but Separate Energy Storage

- Nuclear Thermal Upper Stage

Beamed Energy

- Solar Thermal Upper Stage
- Laser Booster
- Microwave Booster

Launch Assist

- Gas Dynamic Guns
- Railguns

Mechanical Assistance

- Space Platforms and Towers
- Space Elevator

Breakthrough Physics

Not Covered

- Skyhook
- Space Escalator
- Rotovators
- Orbital Ring
- Launch Loop
- Space Fountain
- Maglev
- Ram Accelerator
- Slingatron

…

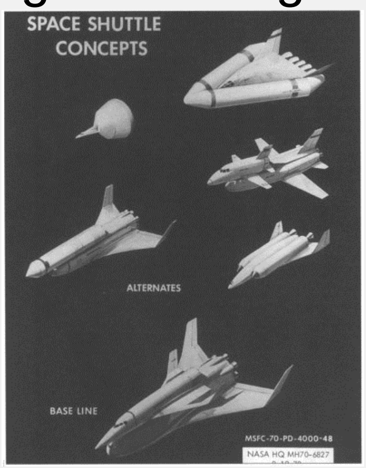
Evaluation Technique

Ideal Process

Concept	Cost	Performance
Rank #1	???	???
Rank #2	???	???

Difficulties

-Large uncertainties.
 Uncertainty > Advantage.
-Large changes in designs.



-Rough performance estimates.
-Cost models inadequate.

Practical Process

•Simple, Systematic Evaluation.
 -Fundamental & Rules of Thumb.
•Subset of Probable & Visible Technologies.
•Accept Researcher's Estimates.
1. Technical Feasibility.
2. Current Status. *(Magnitude of Scaling).*
3. System Advantage.
 -$/kg for payload > 500kg
 -$/kg for payload < 10kg (Nanolaunch)
Only technical considerations.

Technical Feasibility

LTF :	No	Force	Method
nTF :	No	Force	Method

Magnitude of Scaling

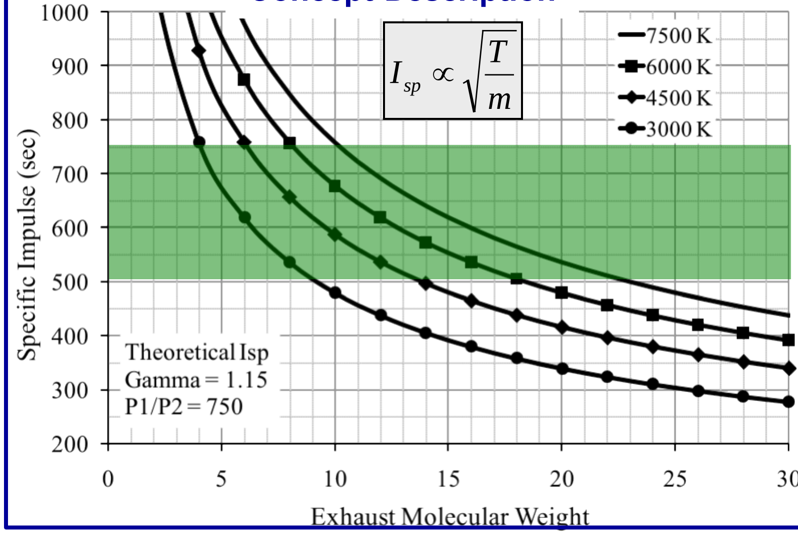
nMS :	>100x	10-100x	<10x
LMS :	>100x	10-100x	<10x

Cost Advantage

LCA :	None	Net?	Clear
nCA :	None	Net?	Clear

Advanced Propellants

Concept Description



Pros

- Higher stored energy.
- Higher reaction temp.
- Higher specific impulse.
- Less fuel.
- More payload or smaller vehicle.
- Fewer stages → SSTO.

Cons

- Low m usually low ρ.
- High E/m less stable.
- Propellant reactivity.
- Much more expensive.
- May need new nozzles.
- Many requirements to meet.

Eval.

LTF

LMS

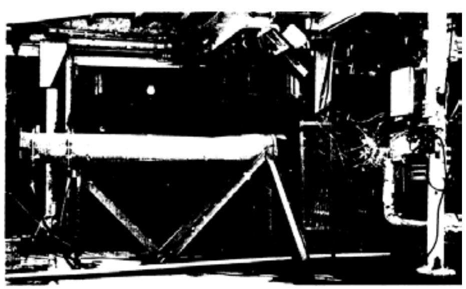
LCA

nTF

nMS

nCA

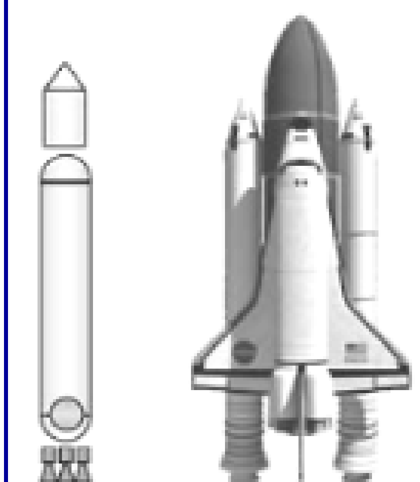
Exemplar Status



$Li/F_2/H_2$
60:1 Nozzle.
Included Mixing.
Isp = 509s
P_c = 750 psia
Th = 8,896N

Lithium-Fluorine-Hydrogen

Envisioned Design



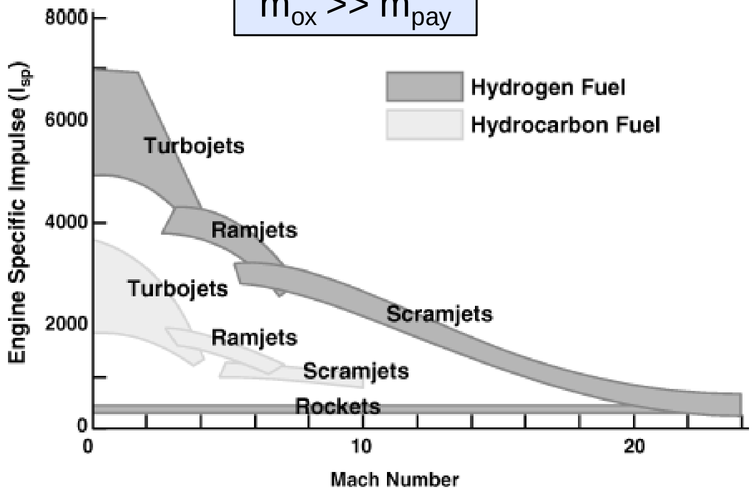
E/m_{mH} = 138MJ/kg
H_2/mH = 3
Height = 50m
m_{pay} = 25MT
GLOW = 126MT
T_{ch} = 3240K
Isp = 911s

Cole: mH Concept

Air Breathing Concepts

Concept Description

$m_{ox} >> m_{pay}$



Pros

- Use atmospheric oxidizer.
- Avoid bringing O_2. (30% for STS).
- More payload or smaller vehicle.
- Advertised at reusable.
- "SSTO"

Cons

- Multiple modes required.
- Flow path integration.
- Ignition/Transition.
- Low Thrust-to-Weight (2 vs. 75)
- Longer flight times.
- Aero-thermal heating.

Eval.

LTF

LMS

LCA

nTF

nMS

nCA

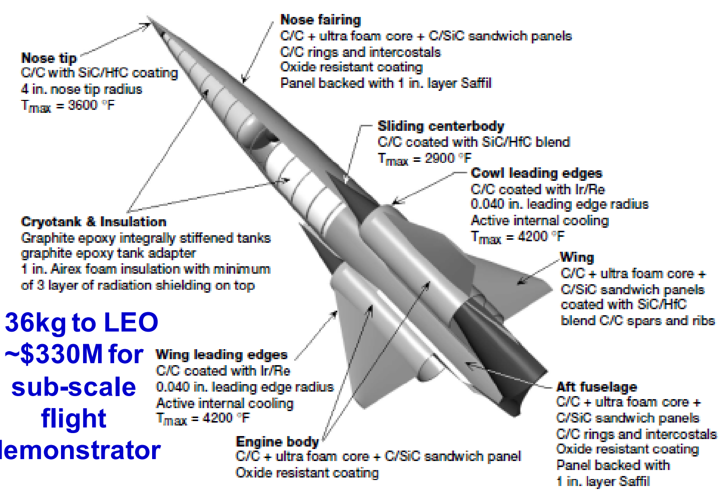
Exemplar Status

Scramjet

- hydrocarbon
- h = 15.2km
- M = 4.5 – > 5.
- 120 kg of JP-7.
- Δt = 140s.
- L = 7.9m.
- m_{dry} = 1814kg.

X-51 WaveRider

Envisioned Design



136kg to LEO
~$330M for
sub-scale
flight
demonstrator

GTX

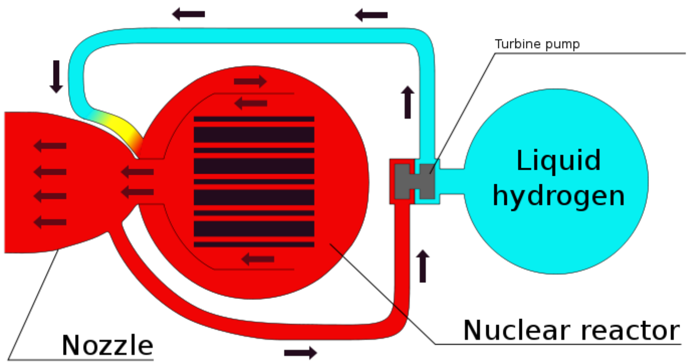
Lazarus (G.Tech): $15,000 /kg @ 12/yr!, ~$6B to first vehicle.

Distribution A: Approved for public release; distribution unlimited.
PA Clearance Number XXXXX

Propellant: Nuclear

Concept Description

- **Fission: 7 x 10^{13} J/kg**
- **Fusion: 6 x 10^{14} J/kg**
- **~10^7 – 10^8 > chemical**



Pros

- Separate energy storage and ejecta.
- Optimized ejecta.
- High Isp
- High T & High Isp upper stage.
- Reduce 1st stage size.
- Enabling for larger interplanetary missions.

Cons

- Inert mass.
- Expensive.
- High T Hydrogen.
- Radioactive Plume.
- Sociopolitical Concerns.

Eval.

LTF

LMS

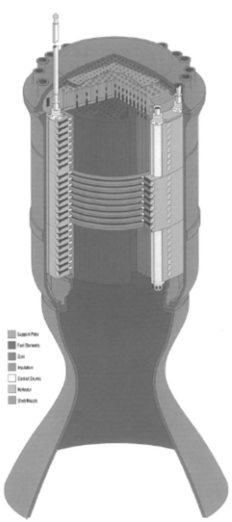
LCA

nTF

nMS

nCA

Exemplar Status



Hexagonal Fuel Elements

Met requirements for manned Mars mission.

Total test time 115 minutes, 24 starts.

Saturn upper stage: 155,000kg to LEO.

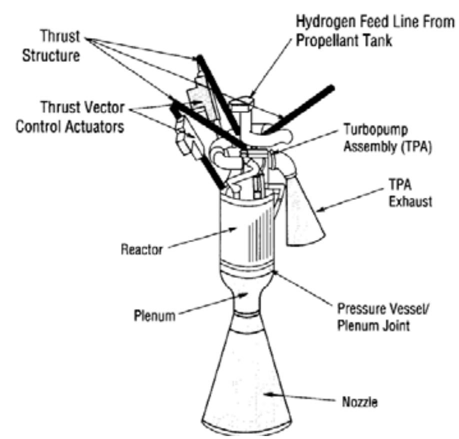
Full power test @ 1100MW.

T_{core}: 2272 K.

25,000 – 250,000lb thrust are validated.

NERVA NRX

Envisioned Design



Pebble Bed

Radioactive Plume

Th/W ~ 25-35:1

T_{ex} = 2750K

Isp = 925-950s

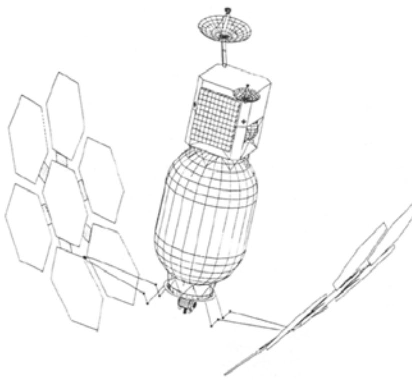
Th = 0.2-0.37MN

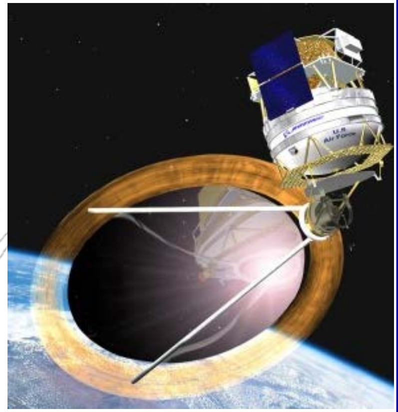
t_{fire} = 200-1050s

SNTP

Solar Thermal Upper Stage

Concept Description





ISUS → → → SOTV

Pros

- Upper stage: propulsion and power for satellite.
- More responsive than EP.
- Moderate F_{th}, high η.
- Step-down launch vehicle
- Save up to 60% cost.
- Titan IV → Delta III save ~$200M.
- Low mass power system
- Thermal storage
- No safety/political issues
- Technology proven in ground tests, TRL = 6.

Cons

- High *T* operation.
- H_2 storage, but methane and ammonia are higher density, lower efficiency options
- 0.1 degree pointing accuracy required
- Temperature change during thruster firing
- May require batteries as well.

Eval.

LTF

LMS

LCA

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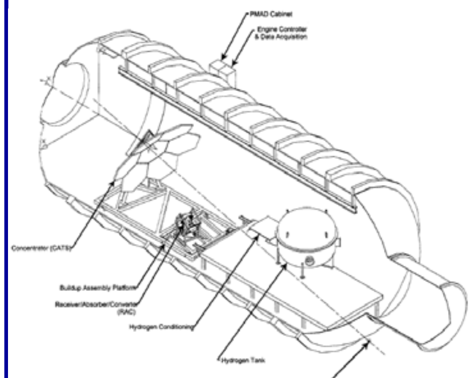
nTF

nMS

nCA

Exemplar Status



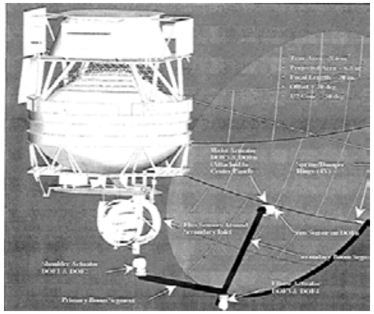
Full ground test completed in 1997; TRL = 6.

- 117 burns, 2-27 min
- 320 hours RAC at T
- I_{sp} = 758 s
- $T_{exhaust}$ > 2000 K
- 90% effective heat exchanger

Tested RAC, system for power gen, distribution, & management, solar concentrator, and cryogen feed/storage

ISUS EGD @ NASA LeRC

Envisioned Design



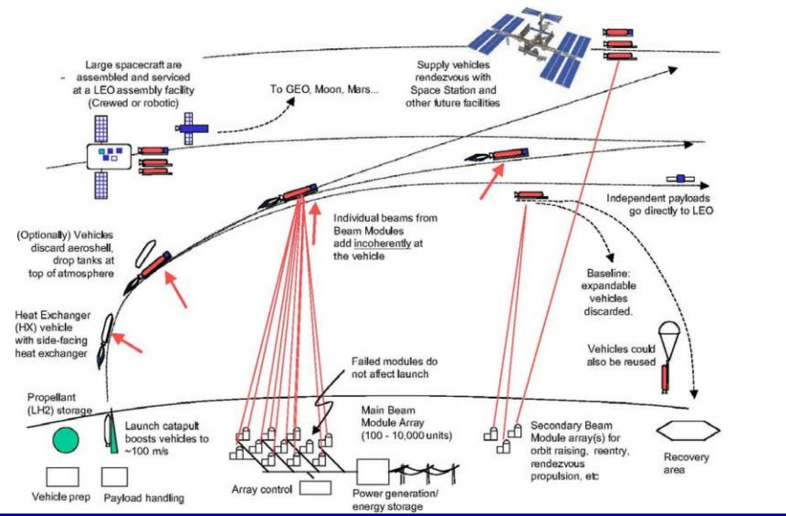
Propulsion, RAC, power systems validated by EGD. Space test planned, 1999…

- Various sizes envisioned
- 14,400 kg, 5000 kg payload
- 160 N @ 800 s Isp
- 30 days LEO – GEO
- 15,000 W @ 100 W/kg thermionics

Uses: Upper stage that stays with satellite, refuelable/reusable stage, move defunct or stranded satellites, delivery to ISS.

Beamed Energy Laser

Concept Description



Pros

- Leave energy storage on ground.
- Better optimized ejecta.
- Higher specific impulse.
- Many candidates:
1. Heat Exchange
2. Plasma Formation
3. Laser Ablation
4. Photon Pressure
- SSTO
- Reusable

Cons

- Low Density Propellant.
- Power Levels ~1MW/1kg in LEO.
- Many Individual Sources.
- High Installation costs.
- Fixed Installation.
- Weather Limited.
- Laser Clearinghouse.
- Aiming/Tracking.

Eval.

LTF

LMS

LCA

nTF

nMS

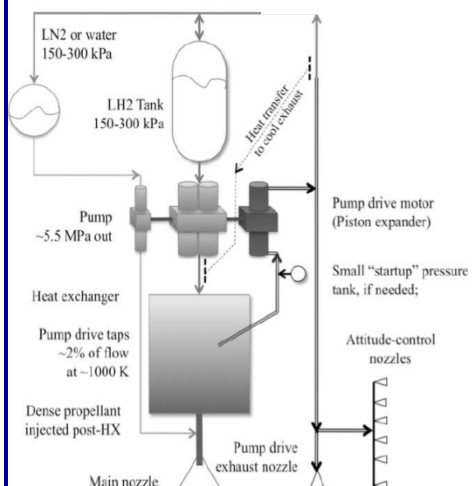
nCA

Exemplar Status

10kW Pulsed CO_2 Laser.
m = 50.62g
d = 12.2cm.
h = 71m.
spin > 10,000rpm.
ΔT = 12.7s.

Lightcraft

Envisioned Design

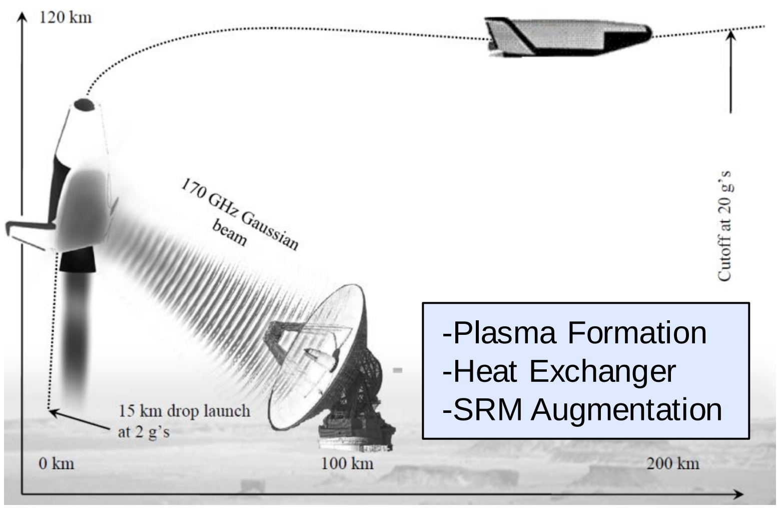


Multiple 10kw fiber lasers.
120-160MW total laser power.
R < 400km.
P/A_{HX} = 10MW/m^2
T_{exit} = 2000K
GLOW = 2800kg.
m_{pay} = 80-100kg.
System Cost ~ $2 Billion

HX Laser Launch

Beamed Energy Microwaves

Concept Description (Parkin)



Pros

- Mass & Energy on ground.
- Better Optimized Ejecta.
- More Payload.
- Low Consumables Cost.
- SSTO.
- Reusable.
- Thorough System Analysis.

Cons

- Low density propellant.
- Power Levels ~1MW/1kg in LEO.
- High installation cost.
- Fixed installation.
- Many sources required.
- Beam attenuation.
- Weather.

Eval.

LTF

LMS

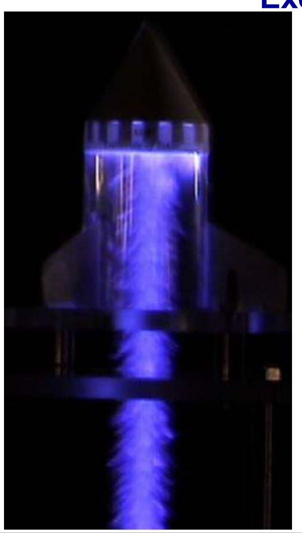
LCA

nTF

nMS

nCA

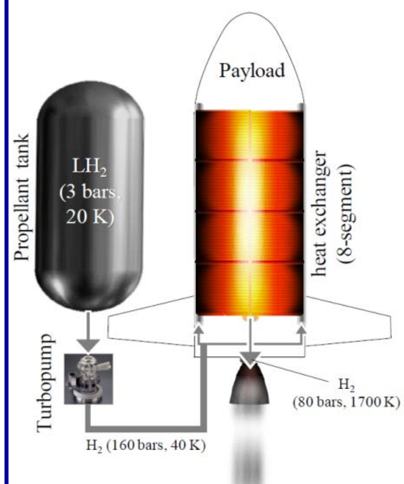
Exemplar Status



P = 1MW
f = 110 GHz
Δt = 0.175ms
C_m = 395 N/MW.
m = 9.5 – 19.5g
Δx = 30cm
h < 0.5m
v_o < 3m/s

Oda

Envisioned Design

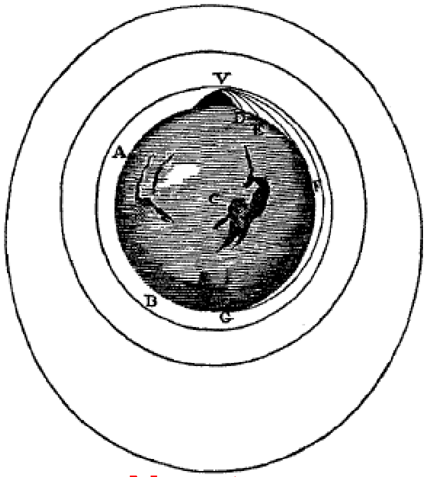


Propellant: LH_2
Isp_{vac}: 800
Th/W: 50
m_{LO}: 636kg
m_{pay}: 30kg
HX size: 3.3x6.7m
P_{HX}: 140MW
f_{mw}: 170 GHz
BF Cost: $760M

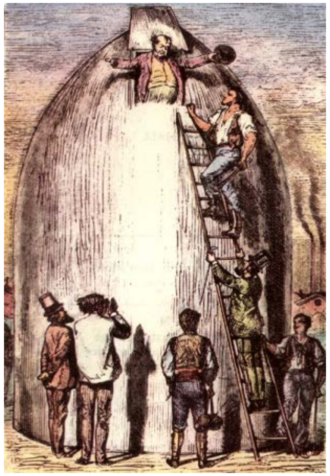
Microwave Thermal Rocket

Launch Assist
Gas Dynamic Gun Launch

Concept Description



Newton



Verne

Pros

- Mature technology.
- Mass & Energy on ground.
- Payload mass fractions.
- Low consumables cost.

Cons

- High T,P Operation.
- a_{peak} ~ 5,000 gees.
- V_{max} ~ 3km/s
- Fixed installation.
- Aero-thermal Heating.

Eval.

LTF

LMS

LCA

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nTF

nMS

nCA

Exemplar Status

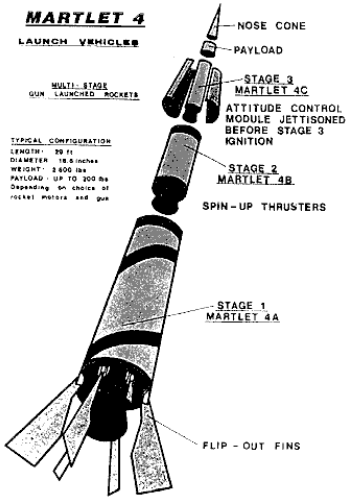
HARP

Stage 1: Gas Dynamic Gun
Stage 2: Solid Rocket Motor

- 570 HARP Shots.
- Demonstrated payloads.
- h ~ 180km
- m ~ 85kg
- V ~ 3.6km/s
- Δt_{reload} ~ 1 hour
- Cost ~ $3000/launch
- Installation cost: $2M (1960s)

-multipoint ignition system.
-fluid filled SRM.

Envisioned Design



HARP & Martlet 4

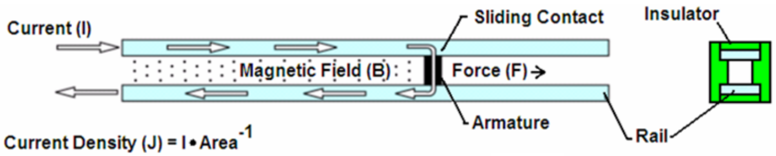
- Gun adequate.
- Martlet improvements.

- m_{shot} = 1300kg
- m_{pay} = 90kg (LEO)
- V = 1.2 – 1.8km/s
- a_{peak} = 5,000 gees.

Project Babylon
2,000kg to 200km
for $600/kg.

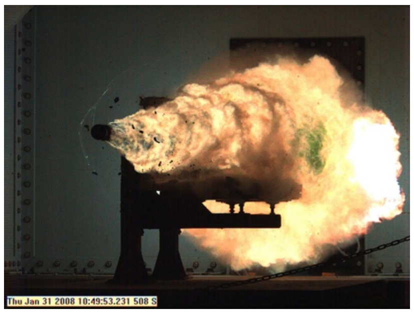
Launch Assist Railguns

Concept Description



Current Density (J) = I • $Area^{-1}$

F = J x B = mass • acceleration



Pros

- Mass & Energy on Ground.
- Increased Payload Fraction.
- Low Consumables Cost.
- Fast Cycle Time.

Cons

- High Acceleration.
- High Installation Cost.
- Pulsed Power System Must be Developed.
- Aero-thermal Loads.
- Fixed Installation.
- Harsh Environment.

Eval.

LTF

LMS

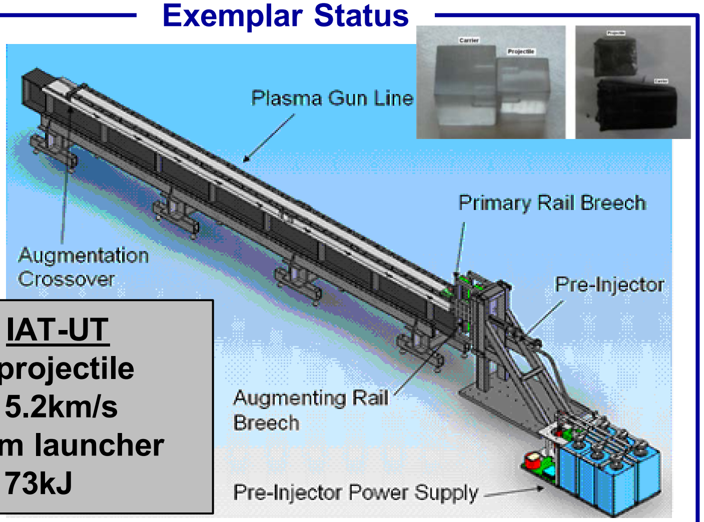
LCA

nTF

nMS

nCA

Exemplar Status

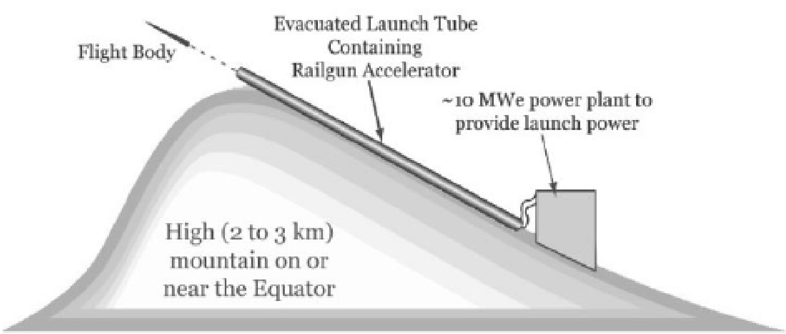


IAT-UT
5.4g projectile
V_{ex} = 5.2km/s
L = 7m launcher
E_{ex} = 73kJ

IAT-UT

Envisioned Design

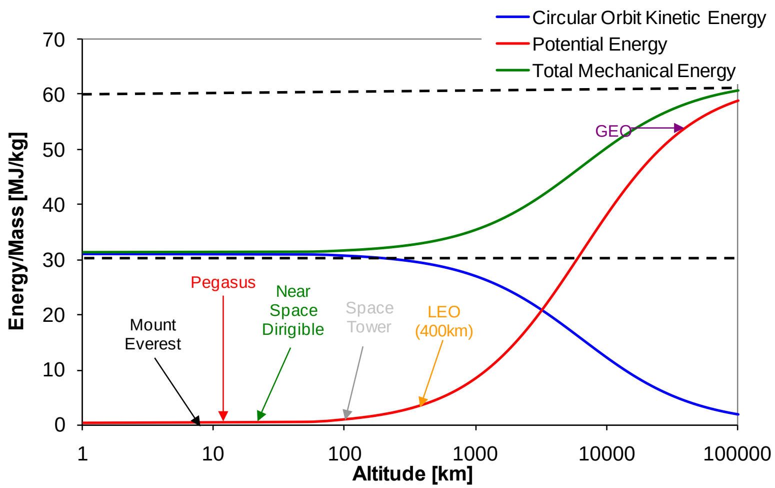
- V > 7.5km/s, E > 10GJ, m_{pay} = 250kg, L > 1km, System cost > \$1B, 10,000 launches → \$530/kg.



IAT-UT

Space Platforms and Towers

Concept Description



Pros

- Above atmosphere.
- Above winds.
- Minor ΔV benefit.
- Multiple candidates.
  1. Solid
  2. Inflatable
  3. Electrostatic

Cons

- Extreme materials requirements.
- Must Support Launch Vehicle & Launch.
- Winds/Weather.
- Single Launch Site.

Eval.

LTF

LMS

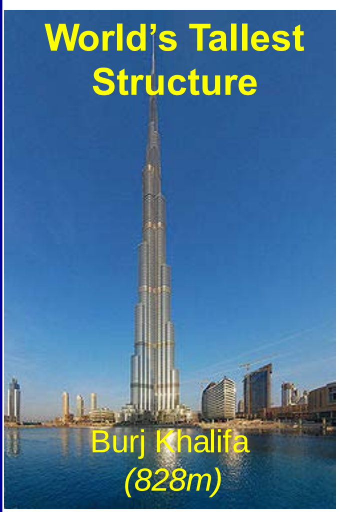
LCA

nTF

nMS

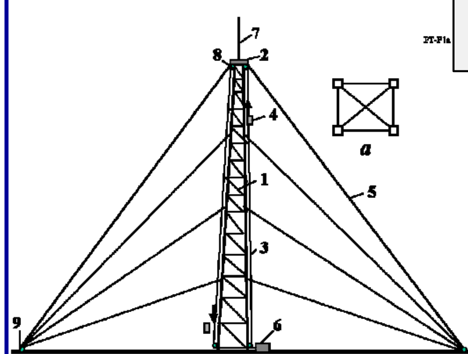
nCA

Exemplar Status



Envisioned Design

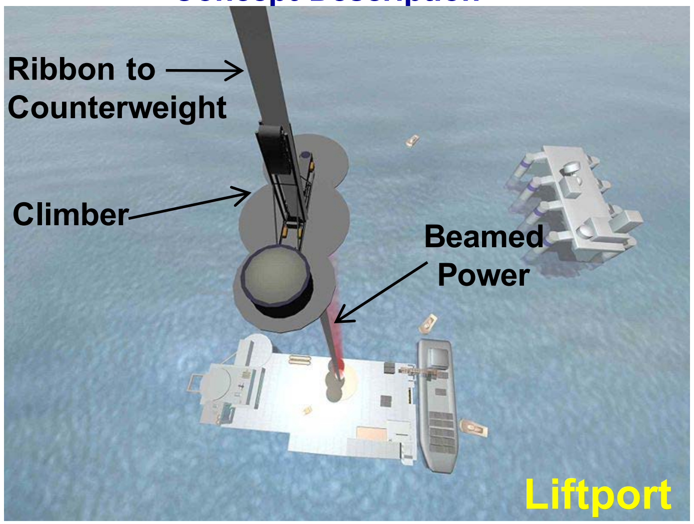
h = 100km
Steel?
t_{build} < 1yr
Cost: "cheap"



Bolonkin

Space Elevator

Concept Description



Pros

- No stored energy required.
- No propellant/launch.
- Low consumables.
- Reusable.

Cons

- Long tether.
- L ~ Xx C_E
- Tensile Strength (~100GPa)!
- Installation Cost.
- Micrometeroids/Debris.
- Weather.
- Atomic oxygen.
- Power/Beaming Efficiency.

Eval.

LTF

LMS

LCA

nTF

nMS

nCA

Exemplar Status

Space Elevator Games

h = 1km

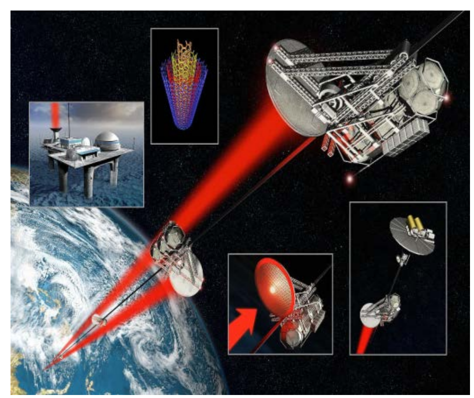
v_{cl} = 2m/s

η_{DC-DC} = 10%

P_{cl} = 1kw.

LaserMotive

Envisioned Design



$C_{D\&B}$ ~ $10B.

C_{elec} ~ $250/kg

$t_{D\&B}$ = 15 years

1m wide ribbon.

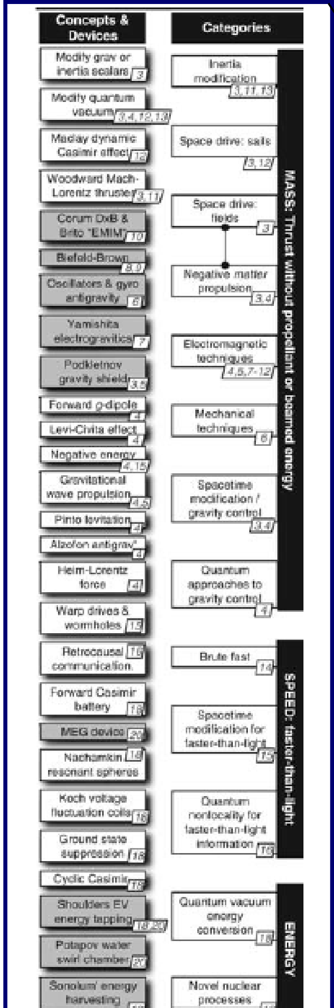
T_{climb} = 8days.

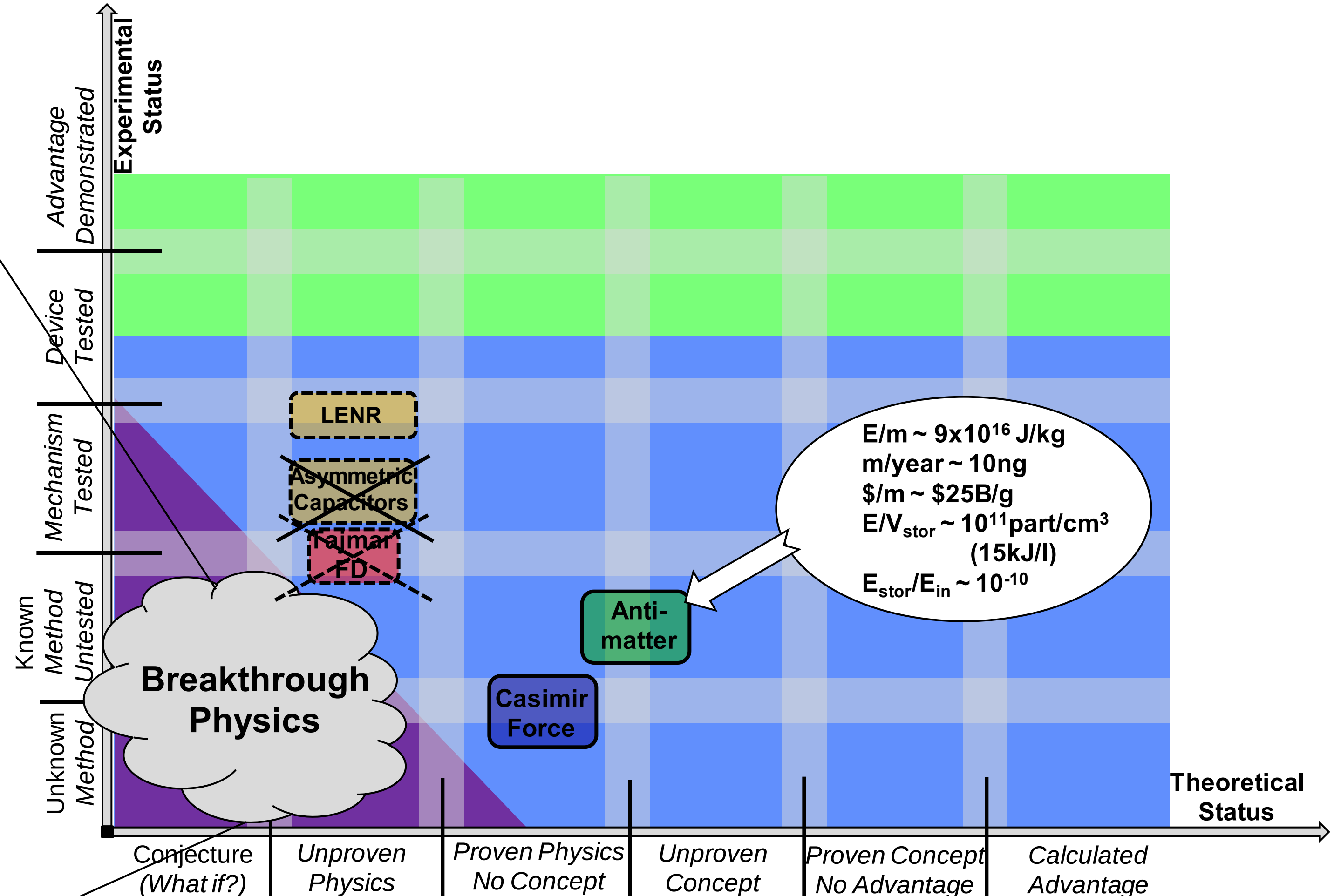
m_{pay} = 11,800kg

Brad Edwards

Breakthrough Physics

Millis, 2009





- Large Number of Concepts.
- Some May be Useful for Propulsion in the Long Term.
- Nothing Immediately Applicable to Saving $$$.

Summary for Launch

Concept	LTF	LMS	LCA	Primary Challenges for Launch	Alternative Mission
Advanced Propellants				Many Requirements, Harsh Conditions, Storage.	---
Air Breathing				Thermal Loads, Time-scales, Th/W.	---
Nuclear Thermal				System Mass, Hot Hydrogen	Space Tug
Solar Thermal				Hydrogen Storage, Hot Hydrogen.	Space Tug
Laser				Aiming, Absorbing, Operations.	---
Microwave				Beam Combining, Propagation, μW conversion.	---
Gun Launch				High gees, Power Sources, Aerothermal Loads.	Rapid, Robust Payload
Railgun				High gees, Power Sources, Loads, System.	---
Space Platforms				Unfeasible.	---
Space Elevator				Materials, O, μmeteoroids, weather, vibrations..	Asteroid Mining
Breakthrough Physics				No known feasible concepts.	---

- **Save $ "Now".** Solar Thermal Upper Stage.
- **Build "Now".** NTP Upper Stage, Gun Launch.
- **Research Now.** BEP (Laser, Microwave), Launch Assist, Adv. Propellants.
- **Avoid.** Complexity, Multiple Breakthroughs,
- **Alternative Missions.** Space Tug or Rapid Delivery of Robust Payloads.

Summary for nanoLaunch

Concept	NTF	NMS	NCA	Primary Challenges for Launch	Alternative Mission
Advanced Propellants				Many Requirements, Harsh Conditions, Storage.	---
Air Breathing				Thermal Loads, Time-scales, Th/W.	---
Nuclear Thermal				System Mass, Hot Hydrogen	Space Tug
Solar Thermal				Hydrogen Storage, Hot Hydrogen.	Space Tug
Laser				Aiming, Absorbing, Operations.	Rapid, Small Payload
Microwave				Beam Combining, Propagation, μW conversion.	Rapid, Small Payload
Gun Launch				High gees, Power Sources, Aerothermal Loads.	Rapid, Robust Payload
Railgun				High gees, Power Sources, Loads, System.	Robust, Small Payload
Space Platforms				Unfeasible.	---
Space Elevator				Materials, O, μmeteoroids, weather, vibrations..	Asteroid Mining
Breakthrough Physics				No known feasible concepts.	---

- **Save $ "Now".** NONE.
- **Build "Now".** Gun Launch.
- **Research Now.** BEP (Laser, Microwave), Launch Assist, Adv. Propellants.
- **Alternative Missions.** Space Tug or Rapid Delivery of Many Small Payloads.
- **Cubesat Paradigm.** (simple, specs., accepted risk, cheap) must be kept.